REPORT ON THE TIME AND FREQUENCY ACTIVITIES OF THE TIME SERVICE DEPARTMENT OF THE U.S. NAVAL OBSERVATORY

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Abstract

Almost every aspect of USNO operations is being upgraded with a view to improving the stability and robustness of our Master Clock. One important motivation for this effort is the projected requirements of many real-time users, the best known among them being GPS.

1 THE BASICS

The most important part of the USNO Time Service Department is its staff, which currently consists of 28 employees. Although we are always attempting to create positions so we can do more things, the loss of highly skilled workers is always a problem. The distribution of the staff by task is one way to characterize what goes on. We have attempted to create such a distribution in Table 1, which is what we predict will be the situation next March. The largest group, about half the staff, is directly involved in time transfer.

Table 1. Snapshot of personnel distribution by task.

Administrators	2
Sécretary	1
Engineers and Technicians	4
Computer Scientists	2.5
Timescale Operations and Development	3
GPS, WAAS and LORAN Monitor Operations	6
NTP Program	.5
Carrier Phase GPS	1
TWSTT	4
Atomic Clock Development	4

The stability of our timescale is based upon our clock ensemble. We currently have 72 HP5071 cesium clocks and 16 cavity-tuned "Sigma-Tau/Datum" hydrogen masers, which are located in two Washington, D.C. buildings and also at the USNO Alternate Master Clock (AMC), located at Schriever Air Force Base in Colorado. The clocks used for the timescale are kept in 19 environmental chambers, whose temperatures are kept constant to 0.1 degree C and whose relative humidities (for all masers and most

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14. ABSTRACT **Almost every aspect of USNO operations is being upgraded wi&h a view to improving the stability and robustness of our Master Clock. One important motivation for this effort is the projected requirements of many real-time users, the best known among them being GPS.**			
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cesiums) are kept constant to 1%. Our timescale is based only upon the Washington, D.C. clocks. As of 29 November, 57 standards were weighted in our timescale computations.

We are also constructing a cesium fountain, which has a measured stability of 1×10^{-15} at 1 day; ordering parts for a rubidium fountain; and anticipating the delivery of a Jet Propulsion Laboratory (JPL)-built linear ion trap mercury standard (LITE) within the next year **[1]**.

Our Washington site recently upgraded its clock measurement system so that all signals are transmitted via temperature-compensated cables with SMA connectors. Our operational system is based upon switches and counters that compare each clock against each of three master clocks once per hour and store the data on multiple computers, each of which generates a timescale and is capable of controlling the master clocks. The measurement noise is about 25 picoseconds (ps), which is less than the variation of a cesium standard. Masers are also measured using another system manufactured by the Timing Solutions Corporation, which is used to generate comparisons every 20 seconds, with a measurement noise of 2 ps. For robustness, the low-noise system measures each maser two ways, with different master clocks as references. All clock data, and time transfer data, are gathered by redundant parallel computer systems that are protected by a firewall and backed up nightly on tape.

Our Master Clock (MC) provides the realization of UTC (USNO), and this is through a frequency divider (1-PPS generator) fed by a 5 MHz signal from an Auxiliary Output Generator (AOG), which outputs the signal of a cavity-tuned maser steered to a timescale that is itself steered to UTC **[2-4]**. The MC has a backup maser and AOG in the same environmental chamber. A second master clock (mc), fully duplicating the MC, is in an adjacent chamber and steered using the same algorithm as the MC. In a different building, we have the same arrangement for a third mc, which is steered to the MC. Its backup AOG is steered to a timescale, based only on clocks in that building, which is itself steered to the MC.

An important part of our operations is our Alternate Master Clock, located at Schriever AFB in Colorado, adjacent to the GPS Master Control Station. We work very hard to keep close communications between our two sites; it is no accident that the three people who work there are not listed separately in Table 1. We also keep the AMC's mc in close communication with the MC; using Two-Way Satellite Time Transfer (TWSTT), the difference is often less than 1 nanosecond (ns). Although the fundamental steering has always been based upon Linear Gaussian Quadratic control theory **[5]**, we are always finding ways to improve our algorithms **[6]**. We have not yet integrated the three masers and 12 cesiums at the AMC with the D.C. timescale, but it remains a possibility that the GPS carrier-phase technique can be made reliable enough to attempt this.

2 THE TIMESCALE

Switch data from the USNO clocks are used to generate timescales using an algorithm due to D. Percival, which averages frequency data from clocks that have been detrended by removing the clock's frequency rate and drift using the unsteered average of detrended cesiums as a reference **[7]**. The integrated frequency scale is then steered to UTC using linear extrapolations from the most recent Circular T from the Bureau International des Poids et Mesures (BIPM). Algorithms with averaging times between 45 and 90 days can be used to predict UTC-UTC (USNO) with an accuracy of 5.6 ns RMS 30 days in advance **[2]**. The integrated frequency scale is currently steered so as to remove about half its time and frequency difference with UTC within 30 days, with the minimal amount of control ("gentle steering")**[4]**. This strategy avoids excessive frequency variations in the Master Clock, while producing an RMS of about 5 ns in UTC-UTC (USNO) last year. In particular, simulations have shown that gentle steering does not perceptibly degrade UTC (USNO)'s stability over periods of 0 to 10 days **[3]**, and this is consistent with

user requirements. In order to assist any users desiring greater long-term frequency stability, it is possible to download the USNO "maser mean" from our Web pages. Although UTC (USNO) itself is a real-time realization of UTC, USNO Web pages also provide real-time predictions of UTC-UTC (USNO) , which are accurate to 3 ns RMS 15 days after the last Circular T point.

Figure 1 shows the long-term performance of the Master Clock. The interplay between time and frequency stability is apparent. It is to be stressed that even before our switch to gentle steering, on MJD 51369, none of the changes described in the figure caption significantly affected the short-term stability of the MC, which is what is needed by navigational users, and many other users of UTC (USNO). Figure 2 shows the current stability of the MC when measured against our maser mean using our low-noise system.

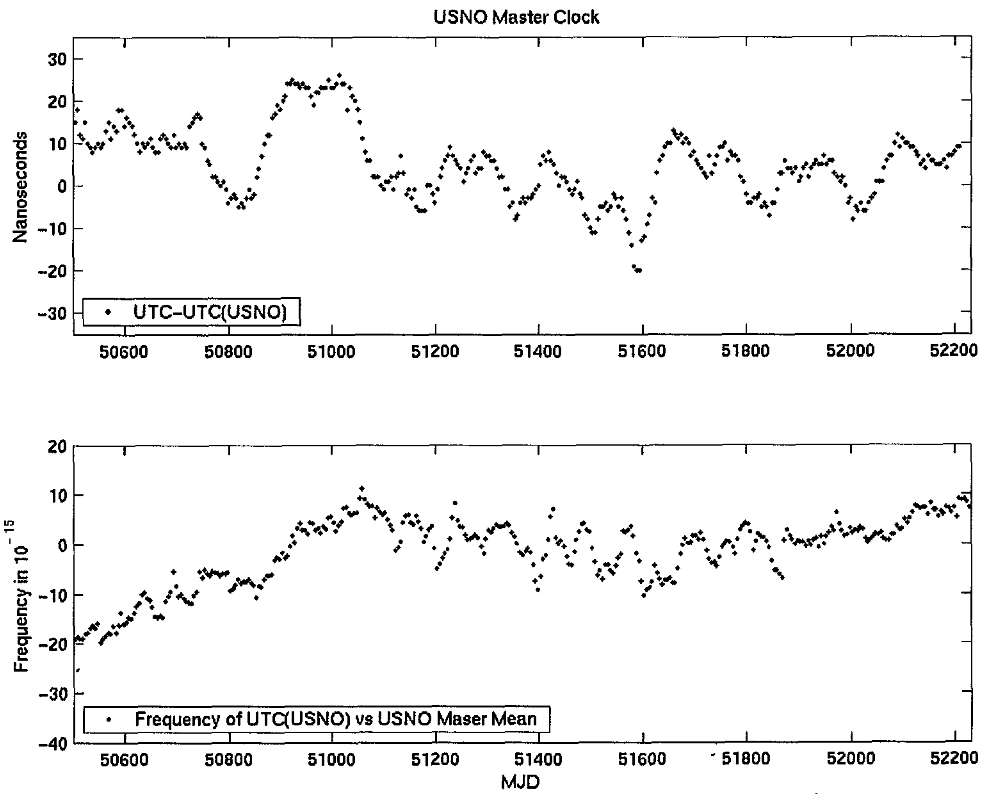

Figure 1. Interplay between time and frequency stability. Top plot is UTC-UTC (USNO) from the Circular T. Lower plot shows the frequency of the Master Clock referenced to the maser mean. The rising curve previous to MJD 51000 is due to the graduated introduction of the 1.7×10^{-14} blackbody correction to the primary frequency measurements. The steering time constant for the time deviations between the Master Clock and the mean was halved to 25 days on MJD 51050. For the last year, the mean has been usually steered so as to remove only half the predicted difference with UTC each month.

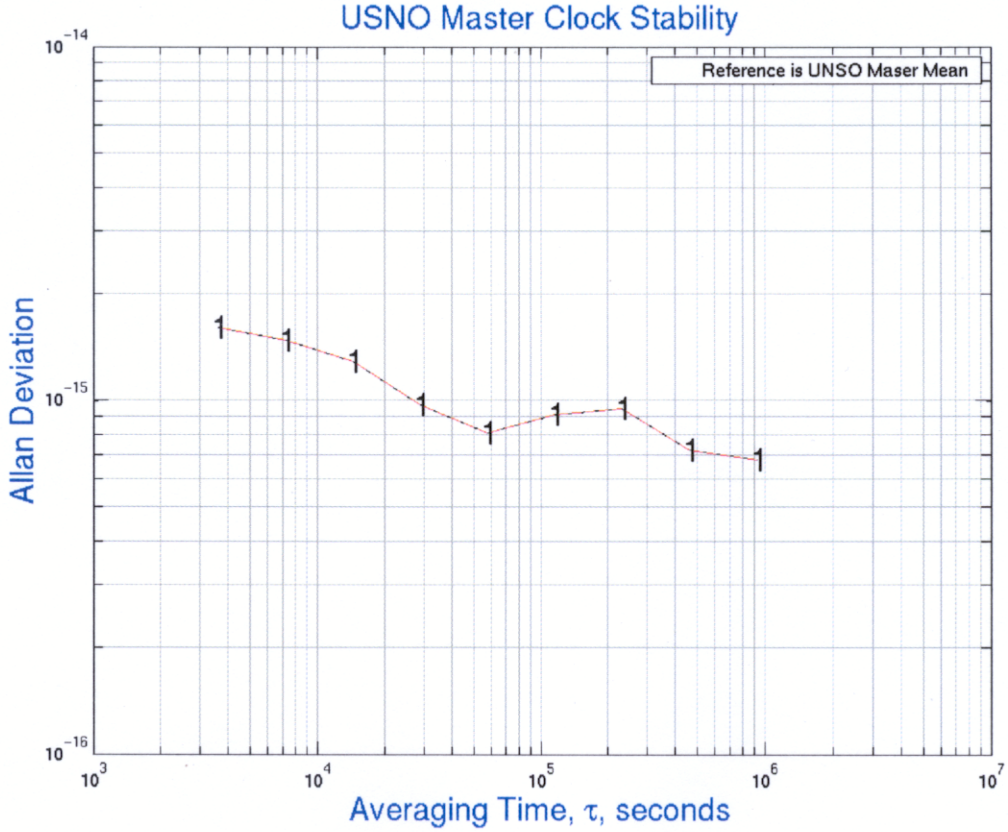

Figure 2. Short-term stability of the USNO Master Clock, referenced to the USNO maser mean.

The operational unsteered timescale (A.1) is based upon averaging only the better clocks, which are first detrended using past performance. As a result of a study reported last year **[8]**, we have widened the definition of a "good clock" and are recharacterizing the clocks less frequently. We are also continuing to work on developing algorithms to optimally combine the short-term precision of the masers with the longer-term precision of the cesiums and the accuracy of TAI itself. The general idea of a future algorithm will be to steer the MC to a timescale based only upon masers, which is steered to a cesium-only timescale that itself is steered to UTC. The steered cesium-only based timescale would either be based upon the Percival Algorithm, or a Kalman-filter algorithm **[9]**. Individual masers could be steered to the cesium-only timescale before being averaged to create the maser-only timescale.

3 TIME TRANSFER

The greatest number of our users are those with the least precise requirements, and we consider it just as important to meet their needs as those of our highest-precision users. Table 2 shows how many times we were queried by various systems. The fastest-growing service is NTP; the number of individual requests we received last year was more than double the preceding year. These billions of requests correspond to at least several million users, and the number grows continuously. The number would be much larger if we counted the NTP-like service requests (through telnet ports 13 and 37). Along with our public service, we also have an NTP service on the SIPRNET, and we are now developing an authentication service for Department of Defense users.

Table 2. Yearly access rate of low-precision time distribution services.

USNO is not compensated for these services.

Telephone Voice-Announcer	820,000
900-number service	60,000
Leitch Clock System	110,000
Telephone Modem	710,000
Web Pages	200,000
Network Time Protocol (NTP)	34 billion

Greater precision is required for two services for which USNO is the timing reference: GPS and LORAN. Data are provided daily to those systems so that they can steer to UTC (USNO), and LORAN is also developing a system so it can steer using UTC (USNO) via GPS. USNO has worked with a manufacturer to develop an all-in-view dual-frequency code and carrier-phase GPS PPS receiver, the TTR-12 [10]. Our operational setup will be based upon temperature-compensated cables and have flat-passband, low-tempco antennas [11-13]. In addition, USNO has also upgraded its single-frequency SPS receivers from TTR-6 to the BIPM-sponsored Motorola units. In order to reduce multipath, a 4-meter tall structure was built for the purpose of mounting GPS antennas higher than the dome on our roof (Figure 3); however, we have also funded the development of a beam-steered antenna, which can eliminate multipath effects directly (Figure 4 and [14]).

The low noise and all-in-view capabilities of the TTR-12's make it possible to contemplate increasing the frequency of our daily GPS monitor information uploads to the Second Space Operations Squadron (2SOPS) at Schriever AFB from daily to perhaps every 15 minutes. This should improve the stability of UTC (USNO) via GPS considerably, and also give some improvement to the stability of GPS Time as well. One issue we have not resolved is how to ensure the robustness of an automated system, but it is clear that a large part of the answer will be in multiple hardware arrangements.

Although not directly required by frequency transfer users, all users ultimately benefit from calibrating a time-transfer system, because repeated calibrations are the best way to verify long-term precision. For this reason, we are working with NRL, BIPM, and others to establish absolute calibration of GPS receivers [15-16]. Although we are always trying to do better, bandpass dependencies, subtle impedance-matching issues [17], power-level effects, and even multipath within anechoic test chambers could preclude significant reduction of the 2.5 ns/frequency 1-sigma error reported in [15]. Since this error is largely uncorrelated between the two GPS frequencies, the error in ionosphere-corrected data becomes 6.4 ns, and experimental verification by side-by-side comparison contributes an additional square root of two. For this reason, it seems that relative calibration, by means of traveling GPS receivers, is a better operational technique. As always, care must be taken that there are no systematic multipath differences between antennas. We strongly support the BIPM's relative calibration efforts for geodetic GPS receivers [18], and in particular are looking forward to comparisons with the multipath-free TWSTT calibrations.

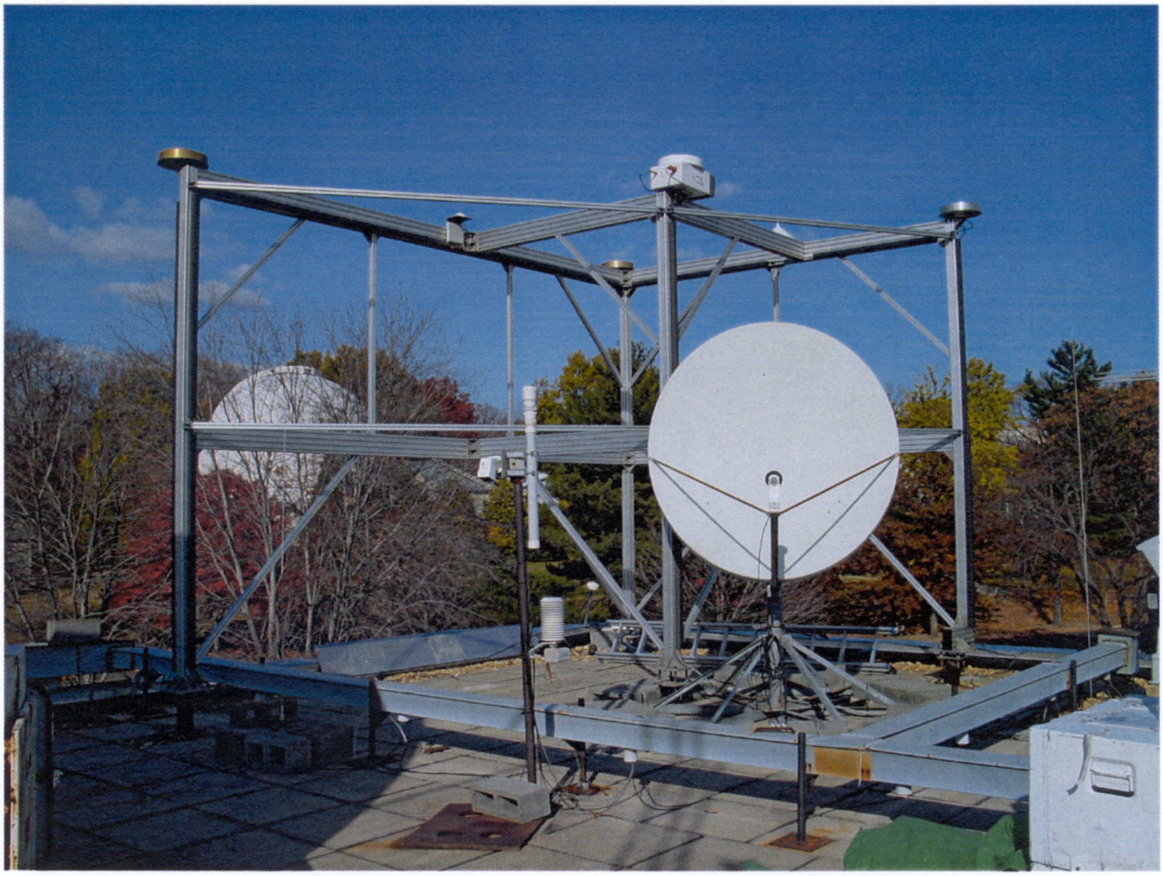

Figure 3. GPS antenna mount. Right of center is a directional antenna used to monitor Wide Area Augmentaion System (WAAS) signals.

The most accurate means of operational long-distance time transfer is TWSTT **[19]**, and USNO has strongly supported BIPM's switch to it for TAI-generation. Last May we replaced our 16-year-old Mitrex modem used for the links with the European laboratories with a carrier-phase-capable SATRE modem **[20]**. In May 2000, we calibrated the USNO-PTB Ku-band link; however, the change in satellite configuration last March rendered that calibration obsolete. Since then, we have calibrated the USNO-NPL Ku-band link to NPL, England using a temporary calibrated transatlantic X-band link, and we hope to set up permanent calibrated X-band observations with the PTB within a few weeks or months. For improved calibration, we are also implementing loop-back setups at USNO, and we have just received delivery of an improved calibration van (Figure 5). Although intended mostly for operation within the continental United States (CONUS), it is small enough to fit on two types of military transport planes. It also has an improved satellite-finding system and can be upgraded to simultaneously do TWSTT between two sites operating at two different frequencies. Another important development is mobile TWSTT, which is reported in these Proceedings **[21]**.

Figure 5 Sixteen Element HAGR Antenna Array

Figure 4. From reference 14. As of this writing, the system has not been delivered to USNO.

The Time Service Department of USNO has also actively pursued development of GPS carrier-phase time transfer, in cooperation with the International GPS Service (IGS). With assistance from JPL, USNO has developed continuous filtering for timing solutions and shown that it can be used to greatly reduce day-boundary discontinuities in independent daily solutions without introducing long-term systematic variations **[22-25]**. Working with the manufacturer, USNO has helped to develop a modification of TurboRogue/Benchmark receivers which preserves timing information despite receiver resets. Using IGS data, USNO has developed a timescale that is now being tested as a possible IGS product **[26]**. USNO is currently contributing to real-time carrier phase systems run by JPL/NASA **[27]** and the Canadian network **[28]**.

The continuous real-time sampling by highly precise systems will reach a climax when USNO-D.C. becomes a full-fledged GPS monitor site, in cooperation with the National Imagery and Mapping Agency (NIMA). This is currently scheduled to happen in 2004 as part of the Accuracy Improvement Initiative (AII), and we anticipate that NIMA will install improved GPS receivers so that we could provide time directly to GPS, in addition to the frequency we currently provide to the Schriever Monitor Station, through our AMC.

Figure 5. Mobile Earth Station for TWSTT calibration. Small enough to be carried on a C141, it could be equipped to serve as a hop-link by communicating through two different satellites and/or frequencies simultaneously. Its automated pointing system makes it easy to find a satellite in the field.

4 ROBUSTNESS, AND MORE ROBUSTNESS

No system can ever be considered 100% reliable, because the overconfidence involved in declaring it so would render it vulnerable. Despite the unattainability of our goal, we are attempting to maximize the reliability of all aspects of our operations.

The most common source of non-robustness is the occasional failure of our environmental chambers. In order to minimize such variations, and to house our fountain clocks, we are seeking funding for a new building. Our anticipated design calls for it to be half underground, with no large internal heat sources, and thermal control generated by air piped in from either of two immediately adjacent buildings, whose systems are themselves redundantly generated. We expect a funding decision this year, and a building start date that could be as early as 2004.

Every aspect of the Master Clock requires dependable power, and we rely upon an uninterruptible power system (UPS) fed by two external power feeds, each one capable of supplying enough power. Should they both fail, we have two independent sets of battery backups, either one of which can supply power to essential systems for at least 40 minutes. However, we only need them to work for the few minutes required for our two diesel generators to power up, either of which can cover the load for several days using available fuel. Should all this fail, we have local batteries at the clocks, which will last another 8 hours. To further save power, we do not use the UPS for computer terminals, room lights, and non-essential equipment. Although we have never experienced a complete failure of this system, most of the

components have failed at least once. We are now awaiting the delivery of parts so that we can install a third external power feed to give added redundancy.

The common theme in all our improvements has been reliance upon multiple parallel redundant systems continuously operated and monitored. Such a scheme can be no more reliable than the people or system doing the monitoring. For this reason we have also begun to upgrade our computers. The completed scheme envisions two interchangeable computers in two different buildings. Each would be capable of carrying the full load of our operations and sensing when the other has failed so it can instantly take control. Each could access data continuously being stored in either of two mirrored disk arrays in the two buildings, and each of those disk arrays has redundant storage systems so that three components would have to fail before data are lost. In addition, we will continue our daily tape backup of all data, and strengthen our firewall as well.

5 CLOSING COMMENT

A key part of our program is described elsewhere in these Proceedings, and that is the cooperation with the national and international timekeeping community. The new frequency standards and improved time-transfer technologies are heralding an order of magnitude improvement in the timekeeping art. We already have users who are asking for greater precision, and we want to work with them to make it possible.

6 DISCLAIMER

Although some manufacturers are identified for the purpose of scientific clarity, USNO cannot endorse any commercial product, nor can USNO permit any use of this document for marketing or advertising. We further caution the reader that the equipment quality described here may not be characteristic of similar equipment maintained at other laboratories, nor of equipment currently marketed by any commercial vendor.

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